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13. ABSTRACT (Maximum 200 words)

This project has focused on modeling and signal processing for the detection and identification of buried and surface land mines, both metal and plastic. The modeling has been performed through development of a method of moments (MoM) for general conducting/dielectric targets in an arbitrary multi-layered environment. The model accounts for all loss and dispersion associated with real soils. Using the MoM models, we have generated computed synthetic-aperture radar (SAR) imagery for buried and surface mines, with this model data compared very favorably to data measured by the Army Research Laboratory (ARL). Moreover, the models have been employed in an optimal Bayesian processor, in which the real-world uncertainties have been accounted for, including variability in the soil properties and the target depth. For the case of anti-tank mines, the results of the Bayesian processor are very encouraging, demonstrating a dramatic decrease in the false alarm rate, via-a-vis traditional approaches. This suggests that SAR may be a viable technology for mine field detection.

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A. Statement of the Problem Studied

Ground-penetrating radar (GPR) constitutes one of the oldest technologies for subsurface sensing. Most such systems are placed in direct or near-direct contact with the earth surface. A significant drawback of this approach is the lack of "standoff", a particular problem for the detection of buried ordnance (*e.g.*, mines). Moreover, it is time consuming to use such hand-held systems for large-area interrogation over variable terrain and foliage. The US Army Research Laboratory (ARL) has therefore undertaken the development of a synthetic aperture radar (SAR) system, with which significant standoff can be achieved. This system provides surveillance of large areas, the results from which can dictate the smaller regions over which conventional hand-held systems (*e.g.*, electromagnetic induction, conventional GPR, and magnetometers) should be deployed. Therefore, while ideally we would like to use the SAR system to detect and distinguish *each* mine, we are particularly interested in mine *field* detection, over very large areas. Consequently, we need not detect each mine, but rather mine *clusters*. This simplified problem statement still constitutes a significant technological challenge, particularly in highly cluttered (natural and anthropic) environments.

To enhance discrimination between targets and clutter, the excitation should be as wideband as possible. However, it is also essential to operate at frequencies for which adequate soil (and foliage) penetration can be effected, particularly for deeply buried targets or regions in which there has been significant foliage growth (for humanitarian demining, one often must deal with mine fields that have been in the ground for decades). The ARL ultra-wideband (UWB) SAR therefore transmits and receives waveforms with usable bandwidth from 50-1200 MHz. Moreover, this system is fully polarimetric, providing access to HH, HV, VH, and VV imagery.

While radar-based subsurface sensing is an old technology, until recently there has been very little modeling done to characterize expected system performance as a function of mine type and environment. In practice there can be wide variability in the mines deployed and in environmental (background) conditions. Therefore, system performance has historically been anecdotal, with excellent performance under certain conditions and unsatisfactory performance elsewhere. Recently, however, we have developed rigorous electromagnetic scattering models for conducting and plastic mines buried in lossy, layered soil (including, potentially, a top layer of snow). Our models are based on a full-wave formulation of Maxwell's equations, with solution via the method of moments (MoM). The principal challenge to making such an analysis tractable is computation of the halfspace or layerered-medium Green's function, which we have performed efficiently via the method of complex images. Moreover, we have restricted ourselves to targets that can be simulated as a body of revolution (BOR), simplifying computational complexity significantly. While not all mines can be modeled as a BOR, the vast majority of land mines (both conducting and plastic) are accurately so modeled.

The phenomenological insight garnered from such models can guide system design and automatic target detection and discrimination. In particular, we examine the potential of radar-based sensing as a function of mine type and environment, in the

context of target RCS and possible target resonances. These results quantify the dramatic variability in radar performance that can be achieved, depending on the detailed mine and soil characteristics. We also document that system performance for plastic mines can be enhanced significantly by modifying the properties of the surrounding environment (*e.g.*, enhancement of the dielectric mismatch between a plastic mine and soil, induced by increasing the soil water content). Other issues that we explore include system performance as a function of bandwidth, in which the benefits of enhanced bandwidth (resolution) are examined in the context of the attendant loss in soil penetration. Finally, we address the potential of polarimetric sensing of buried and surface land mines. It is demonstrated theoretically and experimentally that the special symmetry properties of land mines (and the lack of such for clutter) make polarimetric imaging attractive.

In addition to using wave modeling to elucidate phenomenology and guide system design, the target models play an important role in detection and identification algorithms. In particular, optimal detectors require an accurate model for the signature of the target in question. For the case of buried mines, until recently one was required to use *measured* signatures for such applications. However, empirical target models for buried mines are of limited value due to the strong dependence of the target signature on the mine type, target depth, and soil properties. We have therefore utilized our simulated target models as integral parts of a detector, with results presented here for data measured by the BoomSAR at Yuma Proving Ground (Yuma, AZ, USA). Results are presented in the form of receiver operating characteristic (ROC) curves. We also address wavelet-based compression techniques which reduce algorithm complexity.

B. Summary of Most Important Results

Although radar is one of the oldest tools for subsurface sensing, until very recently there has been little rigorous modeling of the fields scattered from or the resonances supported by buried targets. This is in large part due to the complexity of such analyses, which have been aided greatly of late by revolutionary increases in computational power. Therefore, for much of its existence, the efficacy of radar-based subsurface sensing has been assessed based on a limited set of measured data, yielding results in some cases that suggested radar is a panacea and, at the other extreme, cases in which radar failed entirely. It is now understood that the utility of radar-based sensing for buried targets is largely dictated by the details of the problem (target and soil) in question, with the advances in modeling providing the key to appropriate radar deployment.

In demining applications, one generally must interrogate a large swath of terrain. Moreover, standoff is of obvious benefit when attempting to locate these insidious targets. Therefore, ARL has focused on development of a SAR-based system that affords both of these desired attributes. Moreover, the ARL BoomSAR operates over ultra-wideband frequencies (50-1200 MHz), simultaneously providing soil penetration and resolution. Synthetic-aperture radar results have been presented for data measured at Yuma Proving Ground, Yuma, AZ. These data were used to confirm our MoM-based scattering models as well as predictions with regard to the polarimetric properties of most

land mines. In particular, we confirmed that mines that approximate a body of revolution (BOR) excite no cross-polarized backscattered fields.

After substantiating the model accuracy, we used the computed target signatures to effect a detector. This detector accounted for the real-world situation in which the expected mines are generally known, but the exact (spatially varying) soil properties and target depths are often not known exactly. Therefore, these latter properties have been treated within a statistical framework, in which the soil properties and target depth are characterized via statistical distributions. Results have been presented in the form of the receiver operating characteristic (ROC) and indicate that such an approach has promise. We accurately detected a large percentage of the mines, at a relatively low false alarm rate. Moreover, the false alarms tended to be spread sporadically throughout the SAR image (based on *a posteriori* ground-truth knowledge), while the correct mine detections tended to be clustered, as expected of a mine field. Hence, SAR appears to be an attractive option for mine-*field* detection. Finally, a wavelet-based optimization scheme was investigated to improve detector efficiency. Results from this preliminary multi-resolution study appear attractive, but significantly greater computational savings can be achieved by exploiting a multi-resolution scheme that is shift invariant (unlike the spatial wavelet transform).

While the SAR detector results are encouraging, there were some disconcerting issues learned as a consequence of the measurements. In particular, the buried *plastic* mines were virtually invisible to the radar and were *not* detected. Since many mines have only trace metal content, this failure is particularly troubling. The near-invisibility of the plastic mines to radar may be traced to the fact that the electrical contrast between the plastic target and soil was insignificant for the examples considered here. However, while the properties of the plastic mine cannot be changed, the electrical characteristics of the soil can. In particular, we have examined the utility of applying water to a suspected mine field, thereby increasing the electrical contrast between the target and soil. This issue was addressed in the context of the scattered-field amplitude as well as with regard to the natural resonances of such targets. For the soil and (representative) plastic target considered, it was demonstrated that this technique potentially has significant utility. This matter is aided by the fact that most anti-personnel mines are buried near the surface, mitigating the increased soil attenuation.

In addition to the weak target-background contrast, making difficult the detection of plastic mines, the SAR image is contaminated by artifacts due to imperfections in the imaging itself (*e.g.*, angle-dependent effects in the transmitted waveform and in the polarization, which do not currently allow image calibration) as well as radio frequency interference (RFI). It is felt that significant improvements can still be accrued in these areas (for example, through better understanding of the antennas), and that the subsequently improved SAR imagery will play an important role in detecting low-contrast (plastic) targets. Hence, while soil modification will play an important role in detecting such targets, it is felt that significant systems-level improvements are also important. While the current manifestation of the BoomSAR represents a notable engineering achievement, it is felt that significant improvements are still possible.

The M20 mines buried to a depth of 15.24 cm were the weakest scatterers detected from measured data in this study. To quantify the complexity of the problem for plastic mines, our theoretical results indicate that the plastic mine had a scattered amplitude roughly 4% that of the buried M20 mine (with the plastic mine placed in the same soil as considered in the measurements, *buried to a depth of only 2 cm*). This scattered amplitude is well beneath the noise (random system noise, imaging artifacts, and RFI) and clutter floor, and explains why the plastic mines were invisible in the imagery. After increasing the water content to 20%, the plastic mine had a scattered amplitude approximately 20% that of the 15.24 cm deep M20. This is still a very stressing target, but with better imaging techniques and better removal of radio-frequency interference (RFI), it may yet be possible to detect plastic mines.

Finally, the matched-filter-like detector, which was so effective for the measured data considered here, implicitly assumes that the air-soil interface is flat. In humanitarian demining, for which the mines may have been in the ground for decades, this interface may be rough (or foliated by randomizing overgrowth). In this case, electromagnetic transmission through and scattering from the interface must be parametrized as a random process. While this has not been a concern for the data considered here, there are many applications for which such a formulation is essential. We have addressed this issue in detail, and future SAR-based investigations will investigate the utility of such a framework, through consideration of measured data.

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Mark McClure (PhD earned June 1998)
Bimba Rao (PhD earned May 1999)

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